Use of a Dynamic Radioisotope Power Source for a Long Duration Lunar Science Rover

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The Radioisotope Power Systems (RPS) Program tasked the Compass Team to evaluate use of Dynamic Radioisotope Power Sources (DRPS) for lunar science rovers. The object was to identify their advantages and challenges as well as to influence the technology developments with flight-type requirements. This was done by using the promising Volatiles Investigating Polar Exploration Rover (VIPER) solar-powered rover mission as a platform to 'swap in' a DRPS.

The resulting design used a 'pickup truck bed' approach which allowed simplified installation and operation of the DRPS while also keeping the forward lunar surface 'blocked' from the DRPS waste heat, which could sublimate the icy surface. It was found that with the Stirling DRPS option the mass is within the planned VIPER lander capability and is comparable to VIPER mass and size (the DRPS replaces large battery pack/solar arrays). The Stirling DRPS option produced ~300 Watts electrical (We) using six general purpose heat source (GPHS) bricks and eight Stirling convertors. Replacing the solar/battery power with radioisotope power allows a continuous presence (instead of six hours) in a permanently shadowed region (PSR) and over 18 months of operations with minimal science impact (rearward surface heating). It was also found that use of a dynamic system, instead of a thermoelectric system, reduces the heat impact on the science environment two-to-three times while still providing sufficient waste heat for the rover systems in the PSR (~ -200°C). The DRPS, along with a relay link (like Gateway), can provide extended access to PSR. The system was also found to be capable of roving for eight hours per day with a range of well over 100 km in 18 months.

I. INTRODUCTION

Permanently shadowed regions (PSR) on the moon hold the promise of almost unlimited water ice resources, but present severe power and thermal challenges for prospecting the resources, much less mining and processing them[1]. The VIPER rover, utilizing only solar/battery power, will explore these PSR, but only for a few hours at a time[2]. A more capable power/thermal system based on a radioisotope heat source would alleviate these limitations. Combined with an almost continuous relay spacecraft (like Gateway[3]), such a system could provide extended access to prospect these areas for many years. This conceptual design study was commissioned to do just that: investigate what a VIPER rover that uses a radioisotope power/heat source (in this case a DRPS.) might look like.

I.A. Study Background and Assumptions

The study objectives were twofold: both to investigate the impacts of using a DRPS on a prospecting rover and to gather potential requirements that can influence the technology developments of a DRPS. The study assumed as much of the VIPER architecture as possible, including the science suite, lander, and landing site. Due to the use of a DRPS and the assumption of a nearly continuous relay link, the concept of operations (ConOps) was changed from VIPER, especially the duration spent inside a PSR (increased from six hours to unlimited) as well as the rover range and lifetime.

The main purpose of this design study was to put a demonstration version of a DRPS on a 'copy' of VIPER to perform science in a PSR, while limiting cost to be consistent with a Class D approach. The requirements also included a launch date in 2029-2030, an initial mission duration of 18 months, a location within a PSR or at the lunar poles, and a Class D risk posture (with an exception for the DRPS, which was single fault tolerant).

The primary goals of the study were to provide full power electrical output from the DRPS for at least 18 months (with an option for up to ten years) and demonstrate its operation under launch, landing, and roving loads. Additionally, there were goals of determining degradation rates in the PSR environment and demonstrating survival in a lunar environment, including sun, shadow, and PSR.

Secondary goals of the design included assessing the impacts of exposing a DRPS to the environment (dust, heat sink, sunlight), assessing the exposure of the lunar surface and science environment to the heating and sublimation from the DRPS heat source, and assessing the impact of the DRPS low level radiation to the science instruments.

The lunar DRPS rover used simplicity of DRPS operation, science gathered (number of drillings, distance traveled/surface mapped), and cost as figures of merit throughout the design.

The design adheres to the guidelines in American Institute of Aeronautics and Astronautics (AIAA) standards[4] for mass growth and margin assumptions. The subsystem leads assign mass growth allowance (MGA) to each component in their subsystem design based on both its level of design maturity and its functional subsystem. On top of this MGA, an additional 15% growth on basic dry mass is carried at the system level to achieve a 'green' rating across the board according to the AIAA Mass Risk Assessment ratings at Authority to Proceed (ATP). Additionally, the team carries 30% margin on the power requirements of all subsystems other than mobility, which carries 5% margin.

I.B. Concept of Operations

I.B.1. Launch and Delivery

The DRPS is loaded into the lander on the pad. The system is then launched on Vulcan/Falcon 9-class launch vehicle. The team assumed that nuclear material will be cleared to launch on these vehicles. While on the pad, a built-in shunt radiator and cooling fans are used. There is a four-day trip to the moon, during which time the rover is assumed to be self-powered using the DRPS. The system lands near Spudis Ridge, providing access to PSR, in sunlight on an Astrobotic Griffin Lander[5] (used as representative due to its selection to deliver VIPER).

I.B.2. Deployment and Exploration

The Compass Team chose the same baseline landing site for the DRPS rover as the planned VIPER to provide both commonality for landing and deployment as well as to utilize the VIPER mission's findings of terrain and science. This would allow for more in depth investigations of the promising VIPER sites.

A notional journey for the DRPS rover is shown in Figure 1. It shows a landing on Spudis Ridge with a journey next to various PSR and even a deep dive into De Gerlache crater and its PSR regions.

I.B.3. Primary Mission

The lander deploys ramps, releases the rover, safes the lander and then shuts down over the course of ten hours. Following this, rover checkout occurs over the course of one day. Communications link is made through the Lunar Gateway for the duration of the mission with an option for direct to Earth (DTE) (~250 kbps). After checkout, the rover descends the ramp and performs the minimum science (drilling) and evaluation over the course of one week.

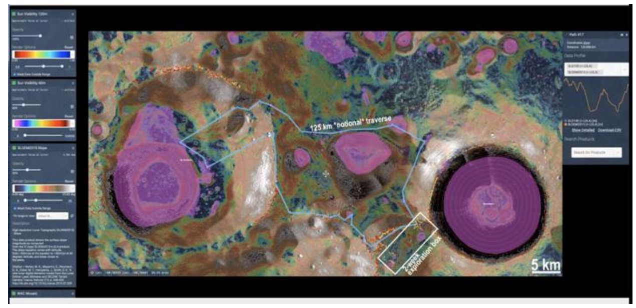

Fig. 1. DRPS Rover Notional Journey

There is an option for real time driving by astronauts on Gateway (less than 1 sec delay), but nominally main operations will be accomplished using waypoint driving and science support from Earth (6 sec round trip delay). The rover will then begin exploration of various craters on Spudis Ridge at 20 cm/s (10 cm/s for hydrogen imaging). More than 100 km of transit distance is expected over 18 months, assuming a slope capability of approximately 15° and four hours of driving time, four hours of drilling and stationary science time, and 16 hours of charge time per day.

The science package consists of a drill, cameras, and three spectrometers from VIPER[2]. 10.5 kg of additional instrument mass and 10 W of additional power was included on top of the VIPER system to allow for the addition of more science instruments. Science investigations are limited to forward of the rover, underneath the rover and below the surface due to the waste heat from the DRPS.

I.B.4. Extended Mission Possibilities

Due to the potential of DRPS power for longer than the 18-month nominal mission, several 'extended mission' options were suggested. The rover could be used to identify easy paths for future in-situ resource utilization (ISRU) rovers, to explore the circumference of many PSR and 'dip' in to conduct science, to explore the floor of large craters (e.g., Shackleton or De Gerlache), or to serve as a relay or navigation asset for future missions. Alternatively, it could capture the deposition rate of volatiles inside PSR over time from lunar atmosphere or lunar impacts. The rover could conduct a test of convertor failure and DRPS recovery. Finally, there are potentials to remove and reuse the DRPS for another lunar mission, use inductive charging to provide power to other surface assets, or provide heat to other assets to survive the night.

II. BASIC DESIGN AND CONCEPT DESCRIPTION

Figure 2 shows the basic subsystem masses for the rover, along with the MGA and margin totals. MGA and

margin totals are shown in green to indicate they meet the qualification for a 'green' rating according the AIAA mass risk assessment.

MEL Summary: Case 1_DRPS_DRM_Rover CD-2021-182	Rover
Main Subsystems	**Basic Mass (kg)**
Radioisotope Power	96.4
Attitude Determination and Control	4.7
Command & Data Handling	18.4
Communications and Tracking	10.7
Electrical Power Subsystem	13.4
Thermal Control (Non-Propellant)	34.8
Science	40.0
Mobility	67.0
Structures and Mechanisms	42.1
Element Total	*327.3*
Element Dry Mass (no prop,consum)	327.3
Element Propellant	0.0
Element Mass Growth Allowance (Aggregate)	53.5
MGA as a %'age	16%
Predicted Mass (Basic + MGA)	380.9
Recommended Mass Margin (Additional System Level Growth) 15%	49.1
Margin as a %'age	15%
Element Dry Mass (Basic+MGA+Margin)	430.0
Element Inert Mass (Basic+MGA+Margin)	430.0
Total Wet Mass (Allowable Mass)	*430.0*

Fig. 2. Mass Summary for the DRPS Rover

Astrobotics's Griffin Lander[5] was assumed to be representative in this case because, as of the date of this study, it is the contracted carrier for the VIPER rover. An estimated payload capacity of 475 kg delivered to the lunar surface was assumed. This lander includes two ramps on opposite sides from which the rover can exit. Figure 3 shows that the rover mass, including MGA and margin fits within the assumed lander capability.

LV Summary: Case 1_DRPS_DRM_Rover CD-2021-182	Single Launch
Architecture Details	**Rover**
Representative Lander	Griffin Lander
Performance (pre-margin)	475
Margin (%)	0%
Total Wet Mass w/15% Growth	430
Available LV Margin	**45**
Available LV Margin (%)	**9%**

Fig. 3. Lander Mass Allowance and Margin

II.A. Concept Description

The Compass Team utilized the mobility system from an earlier iteration of the VIPER design, along with the structural portion of the chassis to reduce overall cost. This also allows the same lander to be used as for VIPER since the interface points to the lander will remain the same along the width and spacing of the deployment ramps. Similarly, the suite of science instruments is also taken from the same iteration of the VIPER design, not only to reduce costs, but to allow for easier comparison of the science output between the solar powered VIPER and the DRPS rover. Figure 4 shows the portion of the VIPER mobility system, chassis, and the suite of science instruments that were used to build the configuration for the DRPS rover design. With the increased lifetime capability, it is assumed that the borrowed VIPER systems can easily be modified to achieve the longer distances and provide longer durations in PSR.

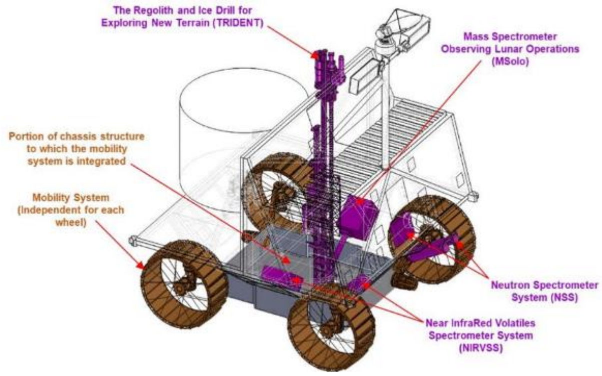

Fig. 4. Elements of the DRPS Rover that were taken from the VIPER design

All remaining structures are designed specifically for the DRPS rover and are driven by the integration of the DRPS as well as maintaining the same volume within the wheel wells to allow the mobility system to fully articulate the wheels as designed. The remainder of the chassis is composed of a space frame integrated to the portion of the structure taken from VIPER and close out sheet panels that enclose the bus to provide a thermally controlled environment. In addition, a structural mast with mechanisms to allow the Nav Cams and lights to both rotate and tilt, two mast reinforcement struts, and a strut system and mounting interface for the DRPS complete the structures subsystem. By utilizing a strut system to integrate the DRPS, heat flow from the DRPS to the interior of the bus, and potentially to the surface below the rover, is minimized. Figure 5 shows these elements.

Fig. 5. Structures specific to the DRPS Rover design

Figure 6 shows the overall dimensions of the DRPS rover design. It should be noted that the wheels shown in all the figures are in the highest position, as they would be while stowed and integrated to the lander deck. It should also be noted that the DRPS shown in the model is a simple cylinder that represents the maximum envelope dimensions

for the central cylinder containing the six GPHS generator, Stirling converters, and the fins utilized for heat rejection.

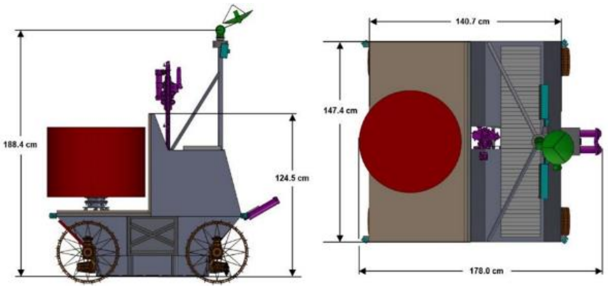

Fig. 6. Overall dimensions of the DRPS Rover

II.A.1. External Rover Components

A number of components, shown in Figure 7, are mounted external to the rover.

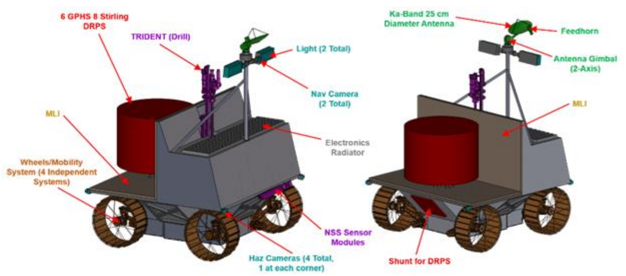

Fig. 7. External components on the DRPS Rover

The DRPS is located near the rear of the rover between and just above the two rear wheel wells. As mentioned earlier, the integration structure is designed to minimize the heat flow from the DRPS to the rover structure, and thus to the other components on the rover, as well as the surrounding lunar surface. The shunt for the DRPS is mounted to the closeout panel located between the two rear wheels of the rover. More details on the RPS design can be found in section III.A.1.

To minimize the waste heat of the DRPS radiating to the surface and the other system electronics, two adiabatic walls of multi-layer insulation (MLI) are included in the design. The horizontal wall below the DRPS minimizes the flow to the lunar surface below the rover while the vertical wall minimizes the heat flow to the system components contained inside the front of the rover, as well as the lunar surface in front of the rover. This is to prevent increasing the temperature of the lunar surface, which would negatively impact science by altering surface conditions prior to the arrival of the rover. Discussion of how the two adiabatic walls will impact the heat rejection from the fins of the DRPS can be found in section III.A.1.

Rounding out the thermal control system is the electronics radiator panel. This panel is located on top of the bus structure between the drill and mast and radiates the waste heat of the electronics contained inside the rover structure upwards and away from the lunar surface. More details on the thermal control system can be found in section III.B.

Located at the four corners of the rover are the four hazcams which are mounted to provide a full 360-degree view around the rover to locate potential hazards to avoid while roving on the surface. The two navcams and two lights are located near the top of the mast and can simultaneously rotate around the mast, providing a full 360-degree view around the rover, as well as simultaneously tilt up and down.

Located at the top of the mast are the Ka-band parabolic dish antenna, feedhorn, and two-axis gimbal. This allows both the antenna and feedhorn to be pointed in the same direction by the gimbal. This configuration allows full hemispherical coverage around and above the rover. Additional details on the communications system design can be found in section III.C.

The Neutron Spectrometer System (NSS) sensor is located at the front of the rover just above and in the middle of the two front wheels. This location ensures that the sensor will obtain readings from the surface that have not been impacted by the rover, whether it be from the wheels stirring up the surface or from the heat rejected from the DRPS. As for The Regolith and Ice Drill for Exploring New Terrains (TRIDENT), much of the drill is located within the bus structure and the top portion of the drill extends out of the top of the bus structure. When drilling into the surface, the drill will extend out through a cutout in the bottom structure of the bus. TRIDENT was located as close to the center of the rover as possible to ensure a relatively even mass distribution of the rover around the drill, providing more stability when drilling into the lunar surface.

II.A.2. Internal Rover Components

The Stirling controller is mounted almost directly below the DRPS to the bottom panel of the rover chassis structure to which the mobility system is integrated. This location not only provided the area to interface the controller to the structure but helps to counteract the Center of Gravity (CG) impact of the relatively high location of the DRPS and lower the overall CG point for the rover. By being almost directly below the DRPS, cable lengths running between the controller and DRPS are shortened and thus are lighter in mass.

The 28-volt power electronics box is mounted to the same panel as the Stirling controller, though up near front of this panel. This location again helps to counteract the CG of the DRPS. The lithium-ion battery is mounted to the face sheet that closes out the bus structure between the front wheels, again helping to move the CG.

The avionics enclosure is mounted just next to the battery on the close out panel between the two front wheels. The inertial measurement unit (IMU), digital video

recorder (DVR), four of the six camera controllers, the NSS electronics box, and all the electronics boxes for the communications system are mounted to the inside of the front closeout panel on the rover bus structure. These locations also help to push the CG point of the entire rover forward to counteract the DRPS location. The rear closeout panel between the two rear wheels is used to mount the electronics boxes for the two rear hazcams. This location minimizes the cable lengths between the cameras and their respective electronics boxes.

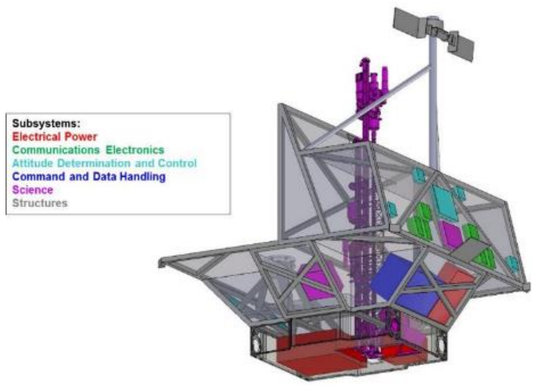

Fig. 8. Internal Components of the DRPS Rover

The Mass Spectrometer Observing Lunar Operations (MSolo) is mounted to the closeout panel located between the front and rear wheel on the left side of the rover. As this portion of the bus is angled, it allows the sensor head of the MSolo to be close to and get a good view of the material being extracted by the drill. The view of the MSolo to the extracted material is provided by the same cutout in the bottom structure that allows the drill access to the surface. The Near-Infrared Volatiles Spectrometer System (NIRVSS) sensor head is mounted directly to the bottom panel of the chassis structure, also having a view of the material extracted by the drill through the same cutout used by the drill and MSolo.

While it is necessary to have this cutout to allow instrument access to the surface below the rover, further analyses are needed to determine the thermal impacts between the lunar surface and the interior of the rover, and potentially the need for a cover or door to close the cutout when not collecting science data. Mounted to the closeout panel located between the front and rear wheels on the left side of the rover is the electronics box for NIRVSS.

A transparent view of the DRPS Lunar Rover showing the internal components is shown in Figure 8.

III. SUBSYSTEM DESIGNS

Most of the rover subsystems were modeled to provide capabilities similar to that of the VIPER rover as described in the configuration section. Thus, these systems are not those specified by the actual VIPER design but were considered sufficient for this conceptual design study. To allow for brevity, only those subsystems with the greatest change from the baseline VIPER rover are described below: power, thermal control, and communications systems.

III.A. Electrical Power System (EPS)

The main focus of this design study was replacing the solar/battery system for short term PSR exploration with a more constant power DRPS. To assess the power requirements, a power equipment list (PEL) was developed, as shown in Figure 11. It is clear from the PEL that most subsystems require power levels in the tens of watts but that the mobility and drill systems each require ~300 We when they are used, which, when combined with the other needs, exceeds the capability of the ~330We DRPS. Thus, a strategy on combining the DRPS with batteries was developed. Figure 9 and Figure 10 show the resulting energy (power x time) needs and energy storage approach that guided the power system design.

Power Modes	DRPS Loading on Pad/ Launch	Lunar Transit and Descent	Rover Checkout	Peak Roving	Roving Science-Sunlit	Drilling Science-Sunlit	Standby Phase	Roving Science-Shadowed	Drilling Science-Shadowed	Standby Phase-In Shadow
Duration (hours)	720	96	24	0.5	8	1	15	8	1	15
Bus Power w/ Growth (W)	47	103	267	568	368	469	156	329	469	100
EPS Parasitic Power (W)	10	10	10	10	10	10	10	10	10	10
EPS Dissipation (W)	0	0	0	17	17	17	8	17	17	8
Total Power (W)	57	113	277	595	395	496	174	356	496	118
RPS Power (W)	315	315	315	315	315	315	315	315	315	315
Total Battery Power (W)	-258	-202	-38	280	80	181	-141	41	181	-197
Battery Energy Consumed (Whr)	**0**	**0**	**0**	**140**	**638**	**181**	**0**	**326**	**181**	**0**

Fig. 9. Energy Requirements by Phase

Operational Phases	Duration (hrs)	Total Power (W)	RPS Power (W)	Total Battery Power Demand (W)	Battery SOC (%)	Total Battery Energy Consumed (Whr)	Ending Battery SOC (%)
Roving Science Phase	8	394.7	315.0	79.7	100.0%	637.6	46.9%
Drilling Science Phase	1	495.9	315.0	180.9	46.9%	180.9	31.8%
Standby Phase	6	173.8	315.0	-141.2	31.8%	-818.5	100.0%

Fig. 10. Energy Balance

The EPS is responsible for generating, storing, and distributing electrical power to the various loads around the spacecraft. Power generation is provided by a dynamic radioisotope power system (DRPS) [The DRPS has six GPHS coupled to eight Stirling convertors. The DRPS takes the heat generated from the GPHS and converts the heat into alternating current (AC) electrical power. A controller monitors and converts the AC power output to 28 V direct current (DC)]. The DRPS generates enough power to meet the load demand during standby operations but cannot support roving operations alone, so an energy storage device is used to provide the peaking load demand as shown by the PEL.

Description	Power Mode 1	Power Mode 2	Power Mode 3	Power Mode 4	Power Mode 5	Power Mode 6	Power Mode 7	Power Mode 8	Power Mode 9	Power Mode 10
Case 1_DRPS_DRM_Rover CD-2021-182	DRPS Loading on Pad/ Launch	Lunar Transit and Descent	Rover Checkout	Peak Roving	Roving Science-Sunlit	Drilling Science-Sunlit	Standby Phase (if necessary)	Roving Science-Shadowed	Drilling Science-Shadowed	Standby Phase- In Shadow
	30 days	4 days	1 day	30 mins	8 hours	1 hour	16 hrs	8 hours	1 hour	extended
	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
DRPS DRM Rover	**86**	**128**	**254**	**564**	**364**	**430**	**174**	**334**	**430**	**132**
Rover	**86**	**128**	**254**	**564**	**364**	**430**	**174**	**334**	**430**	**132**
Radioisotope Power System	**39.0**	**39.0**	**39.0**	**39.0**	**39.0**	**39.0**	**39.0**	**39.0**	**39.0**	**39.0**
Attitude Determination and Control	**0.0**	**0.0**	**54.7**	**54.7**	**54.7**	**11.0**	**7.0**	**54.7**	**11.0**	**7.0**
Command & Data Handling	**28.0**	**28.0**	**28.0**	**47.6**	**49.3**	**49.3**	**20.4**	**49.3**	**49.3**	**20.3**
Communications and Tracking	**0.0**	**42.5**	**42.5**	**42.5**	**42.5**	**42.5**	**42.5**	**42.5**	**42.5**	**0.0**
Electrical Power Subsystem	**10.1**	**10.1**	**10.1**	**30.3**	**30.3**	**30.3**	**15.6**	**30.3**	**30.3**	**15.6**
Thermal Control (Non-Propellant)	**6.8**	**6.8**	**6.8**	**6.8**	**6.8**	**6.8**	**6.8**	**6.8**	**6.8**	**6.8**
Science	**1.6**	**1.6**	**73.2**	**43.2**	**81.2**	**251.2**	**43.2**	**51.2**	**251.2**	**43.2**
Mobility	**0.0**	**0.0**	**0.0**	**300.0**	**60.0**	**0.0**	**0.0**	**60.0**	**0.0**	**0.0**
Structures and Mechanisms	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

Fig. 11. Power Equipment List for DRPS Rover

The energy storage consists of a lithium-ion battery which is discharged during roving and drilling (science) operations which can last up to nine hours continuously per day. The rover will then spend the remainder of the day (15 hours) recharging the battery for the next set of operations. Note that the nine hours of continuous operations is expected to bound the energy storage sizing and may not reflect the real-world operations of the rover and differs slightly from the more conservative ConOps described above.

Power from the DRPS and lithium-ion battery is distributed to the various rover system loads using a 28 VDC architecture with commercial off-the-shelf (COTS) power management and distribution (PMAD) cards. These cards provide battery charge/discharge regulation and fault protection to the various spacecraft loads.

III.A.1 Dynamic Radioisotope Power Source (DRPS)

Dynamic power conversion systems are being considered for future RPS. The advantage of DRPS are higher power conversion efficiencies which reduce the consumption of scarce plutonium (Pu)-238. The Radioisotope Program Office (RPO) is developing three power conversion devices which may be used in future DRPS. Two of the power convertors are based upon the Stirling cycle and the third is based upon the Brayton cycle. SunPower and American Superconductor (AMSC) are developing the Stirling convertors while Creare is developing the Brayton system.

During the development of these convertors some work was performed as to how these power convertors might be integrated into a generator. Based upon the contractor's work, estimates were made as to the mass and power output of a six GPHS, eight Stirling convertor system. Both Stirling generators produced relatively similar mass and power output and a blended performance estimate between the two was made for this study. The Brayton system was not included because of its significant increase in mass and volume over the Stirling concepts. Figure 12 shows two Stirling generator concepts.[6]

Normally the DRPS would be designed to operate in a 4 K deep space environment. Because the primary purpose of this rover is to assess the water content of both the surface and subsurface regolith a heat shield was created to prevent sublimation in front of and below the DRPS. This keeps the waste heat generated during the power conversion process from disturbing any water ice content in front of or below the rover.

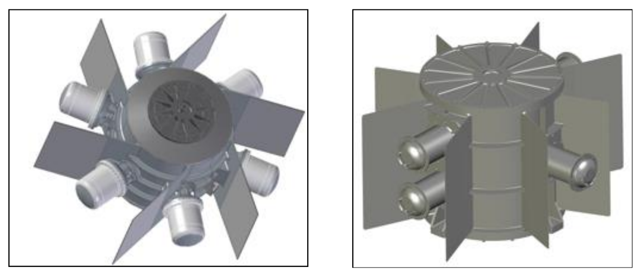

Fig. 12. DRPS Generator Concepts

Due to this heat shield, the effective radiator area is reduced by approximately one third, which decreases the power output of the generator. In a deep space environment, the DRPS should produce about 353 WDC. However, with the heat shield, the DRPS produces a maximum of 335 WDC of electrical power, which decays to 315 W at end of mission (EOM) (4.5 years after fueling). While the mission life for this rover concept is only 4.5 years, the DRPS are designed for 17 years of life (three years of storage, plus 14 years of missions). The DRPS envelope is 0.8 m in diameter and 0.5 m tall with a total heat rejection of 1127 W at beginning of life (BOL). The system has a specific power of 3.8 W/kg, and a mass of 95 kg.

III.B. Thermal Control System

The thermal system is used to maintain the operating temperature of the electronics and other components of the

rover within their desired temperature range. This is accomplished by insulating the rover to minimize heat loss to the surroundings and provide a means of controlled heat rejection if the internal heat production is greater than what is needed to maintain the internal temperature within the desired range. To accomplish this, the main components of the thermal system, include:

- Radiator Panel with louvers for removing the waste heat from the electronics.
- Heat pipes and cold plates for moving the heat from the electronics packages to the radiator.
- MLI to insulate the electronics, as well as provide a barrier from the waste heat of the DRPS to the surface in front of the rover.
- Heaters
- Temperature Sensors, Controllers, Switches, and Data Acquisition

The specifications used to size the thermal control system components is given in Table I.

Table I. Specification for the Thermal System Operation

Specifications	Value/Description
Dimensions: Rover Insulation	Estimated Electronics Enclosure Plus Heat Shielding: Length (l_e):1.0 m, Width (w_e):1.5 m, Height (h_e):1.5 m: Insulation surface area:10.5 m^2
Waste heat	Electronics Systems: 221.5 W
Operating Temperature	Electronics: 300 K
Insulation (MLI)	25 layers of MLI are used to cover all external surfaces for the electronics boxes.
Environment	Lunar Polar (154 K to 50 K) surface temperature range
Radiators	Surface mounted radiator for rejecting heat from the electronics. Louvers are utilized on the radiator to adjust the heat flow to the surroundings between operation outside the crater under sunlit conditions and operation within the PSR.
Cooling	Water heat pipes with cold plates are used to move the heat from the electronics to the radiator.
Heating	Electric heaters are used to provide heating to the internal components as needed.

III.B.1. Surface Heating from DRPS

To effectively evaluate the surface composition, it is necessary that the surface remain in its initial pristine state during evaluation with the scientific instruments. The main reason for this is the heat rejected from the DRPS can heat the surrounding surface raising its temperature and potentially releasing volatiles which would affect the science data being collected, as illustrated in Figure 13.

To determine the effect of the DRPS on the surrounding surface temperature, an analysis was performed to establish the steady state temperature rise of the regolith surrounding the DRPS as a function of distance from the power source. The view factor of the DRPS to the surface and corresponding surface temperature was determined as a function of the distance from the rover. These results, in Figure 14, show that, to keep the regolith in front of the rover in its pristine state (remaining at the ambient environmental temperature of 50 K) while being analyzed, a MLI shield would be needed underneath the DRPS and on the side facing the front of the rover. This shielding will block the view of the surface terrain in front of the rover to the DRPS, thereby maintaining its pristine temperature.

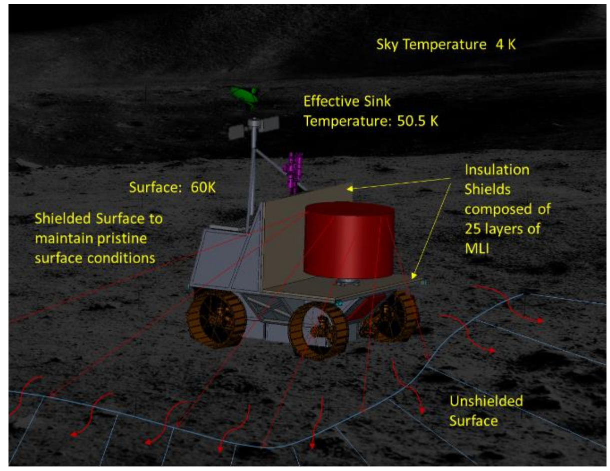

Fig. 13. Illustration of Surface Heating from the DRPS

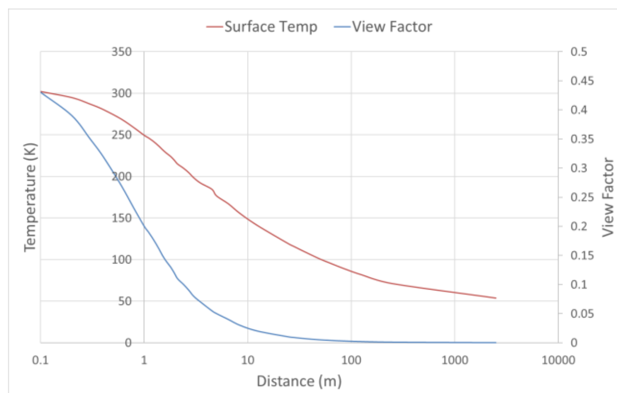

Fig. 14. Steady-State Surface Temperature and Surface View Factor to the DRPS

III.C. Communications System

In order to provide almost continuous communications with the southern polar rover, the planned Lunar Gateway communications link using Ka-Band was assumed. The subsystem design shown in Figure 15 consists of Ka-band communication at 70,000 km away with the Lunar Gateway (or if visible, at 385,000 km away with a 20-m Earth station) via a gimballed 25.4 cm diameter high gain antenna (HGA) parabolic reflector, or a low gain antenna (LGA) feed-horn. The HGA channel information rates to the Gateway are 245 kbps, and from the corresponding LGA channel are 2 kbps. If a line of sight is available from the moon’s south pole to any of the NASA deep space

network (DSN) or any commercial 20 m (or larger) sites, then the achievable information rates through the HGA are 230 kbps, whereas through the LGA they would only be 2 kbps (assuming each channel has 12.7 dB of excess link margin for weather phenomena or higher information rates on a clear day).

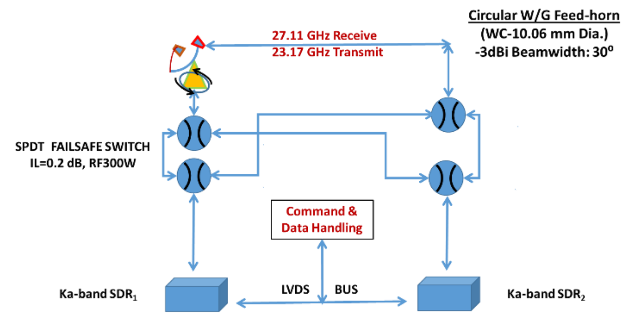

Fig. 15. DRPS Ka-Band Communications with Lunar Gateway

IV. CONCLUSIONS

By replacing the solar/battery power system on a notional follow-on VIPER rover with radioisotope power, a continuous presence (instead of six hours) in many PSR and over 18 months of operations should be possible. The impact of the DRPS on the rover mass was cancelled out by other system changes, mainly the elimination of the large battery pack on the solar powered VIPER design. With such a power system, roving for eight hours per day is possible, with a range of over 100 km in 18 months. Due to the DRPS radiated heat, only science areas in front and below the rover will remain at ambient low temperatures. This will require modifying the science collection process. The external mounting of the DRPS will, however, ease the on-pad installation process and save mass.

While not described here, early cost estimates suggest that this DRPS rover may fit in a Class D cost cap assuming robust VIPER heritage, DRPS as government furnished equipment (GFE), and assuming launch, lander, operations, and nuclear specific costs [National Environmental Policy Act (NEPA), fueling, transport, launch service program (LSP), etc.] are not included.

Further work is required in several areas. The first is to assess what the longer life/distance impact would be on the current VIPER components. In parallel, a more in-depth science ConOps should be developed along with additional science instruments to be carried (10.5 kg/ 10 W of added mass and power were allotted). Lastly, additional thought should be given to how else such a ~300 We rover could be used. Several options could include caching samples, terrain reconnaissance in advance of human crews and even providing crew support auxiliary power.

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